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Forbush decreases in cosmic radiation : effects of solar flares associated with type IV radio bursts and with different field orientations at flare sites

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Abstract : The large scale magnetic fields at flare sites are considered and relative effectiveness of flares with different field orientations on interplanetary parameters and on characteristic features of Forbush decreases are discussed. Type IV burst association of these flares and their importance in producing Forbush decreases have also been discussed. Differences in cosmic ray modulating efficiency of flares with southward/northward directed magnetic fields and those associated/not-associated with type-IV radio bursts have been found. Forbush decreases are more frequently associated with southward flares as compared to northward flares. Most of the flares associated with large increase in IMF intensity and/or solar wind speed and producing large amplitude Forbush-like decreases are also associated with type-IV radio bursts. The results are discussed in the light of models of Forbush decreases including drift effects. An explanation is given to account the observational results.

Keywords : Cosmic ray modulation, Forbush decreases, solar flares, radio bursts

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1. Introduction

Forbush decreases are characterized by a rapid reduction (within a few hours) in cosmic ray intensity followed by a slow recovery typically lasting several days. Since its discovery, Forbush decrease in cosmic ray intensity has been studied by many researchers [1-13]. In several studies of Forbush decreases, attempts have been made to correlate the solar flare-associated interplanetary disturbances and Forbush decreases. These are generally thought to be produced by solar flare-associated interplanetary disturbances. In particular, flares accompanied by type-II and type-IV radio bursts are good candidates that produce them [2,3]. However, characteristics of interplanetary disturbances responsible for such decreases are not fully understood yet and it is desirable to isolate specific factor(s) mainly responsible for this phenomenon [13,14].

The role of solar eruptions and the underlying physics of cosmic ray modulation remain as interesting as ever; one reason being their direct or indirect role for long-term (~11-year) modulation of cosmic rays. They have become more interesting because of the varying evidences that (i) individual solar eruptions can give rise to major cosmic ray modulation events that span the heliosphere [15], (ii) major modulation events result from multiple solar eruptions more or less evenly distributed in ecliptic longitude to span the heliosphere [16], (iii) the most powerful eruptions in each range of longitudes sweep up slower preceding transients and corotating streams to form merged interaction regions (MIR) of limited longitudinal extent; these MIRs themselves overlap with each other at their edges and combine to produce a global merged interaction region (GMIR) that encircles the Sun to produce the observed widespread modulation [17] and (iv) that the large-scale structure of the heliosphere, specially the time evolution of heliospheric current sheet and, consequently, the gradient and curvature drifts are important element of cosmic ray modulation; drift effects are dependent on the polarity of the solar magnetic field [18,19].

A number of workers have studied the role of drifts on long-term modulation ([20-22] and references therein); many of them emphasized the role of gradient and curvature drifts. On the other hand, very few workers [23-25] have studied the role of drifts in the phenomena of Forbush decreases and experimental

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evidences are inconclusive as regards the role of drifts during this phenomenon. In the present work, we have discussed our results in the light of simulations of Forbush decreases including drift effects

The operation of various proposed mechanisms during Forbush decreases such as convection, diffusion, dynamic sweeping of cosmic ray particles out of the inner heliosphere by moving compression wave, adiabatic cooling of the particles, drift of particles due to gradient in and curvature of magnetic field, involves directly or indirectly at least one of the two parameters solar wind velocity and magnetic field strength. Therefore, in this paper, we have also considered the enhancement in these parameters to study the differences in modulating efficiency of flares with southward/northward directed magnetic field and those associated/not-associated with type-IV radio bursts.

It has been reported earlier that there is no appreciable east-west asymmetry in the flare occurrence and a positive north-south asymmetry in its occurrence during the periods considered for this analysis [26, 27] As we have considered solar flares with different properties occurring at different latitudes and longitudes on the solar disk, we have further studied the possible east west, center-limb and north-south asymmetries in the effectiveness of the flares in reducing cosmic ray intensity on the earth. All these results taken together, may also enable us to define a possible scenario, which produces appreciable effects in cosmic rays.

2. Analysis

We have utilized characteristic properties of solar flares observed in southward/northward directed fields at flare-sites during periods 1967-70 [28] and 1978-79 [29]. These periods of study cover two solar maximum conditions and two different conditions of solar polar magnetic fields (the field has reversed completely in 1971) We have studied the relative effect of flares with southward/northward magnetic fields and those associated/not-associated with type-IV radio bursts on the transient intensity decreases, using the method of superposed epoch analysis as well as on individual basis. Eruption dates of these flares have been taken as key (epoch) days for the superposed epoch analysis Interplanetary plasma and field parameters (V and B) after flare eruptions and locations of flares on the solar disk have been considered for detailed analysis.

3. Results and discussion

Figure 1 shows the results of superposed epoch analysis of daily mean cosmic ray intensity data recorded at Deep River neutron monitor, with respect to solar flares observed during 1967-70 and 1978-79, whose flare-site magnetic fields could be determined. In this figure, superposed epoch profiles of cosmic ray intensity with key days corresponding to flares having (i) southward directed fields and (ii) northward directed fields have been plotted. It is evident from this figure that flares having southward directed fields at flare sites are much more effective in producing Forbush decreases than flares with northward directed fields

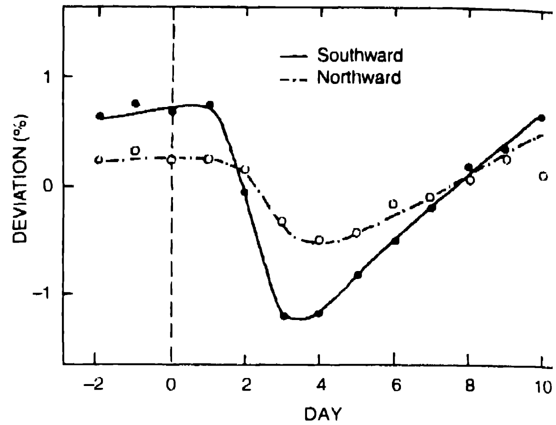

Figure 1. Superposed epoch plots of neutron monitor data recorded at Deep River with respect to key days (zero hour) corresponding to solar flares having southward/northward directed fields at flare-sites

Flares associated with type-IV radio bursts have been shown to be good agent that will produce transient variations in cosmic rays [2,30]. In Figure 2, we have divided our sample of southward flares into two groups, namely, those accompanied with type-IV bursts and those not accompanied by them. Those associated with type-IV bursts are more effective in reducing cosmic ray intensity than flares without type-IV association; this substantiates the results of Iucci *et al* [2].

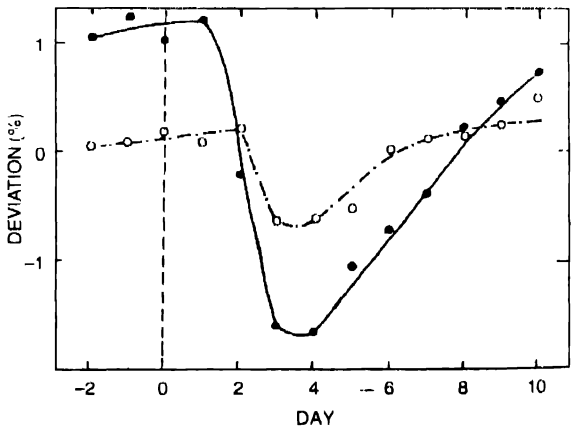

Figure 2. Superposed epoch analysis results of neutron monitor data Zero epochs correspond to southward-directed flares, with type IV radio burst (solid circles) and without type IV radio burst (open circles)

In addition to studies based on superposed epoch analysis, we have also seen the effects of southward/northward flares and those associated/not-associated with type-IV radio bursts on transient modulation of cosmic ray intensity on the basis of individual events. Interplanetary parameters, solar wind velocity and IMF strengths, during these events have also been considered. About 75% of flares that took place in southward-directed fields and accompanied by type-IV bursts are able to produce appreciable decrease in cosmic ray intensity. Moreover, flares responsible for Forbush-type decreases are also accompanied by large increase in IMF strength and solar wind speed. Further, flares with southward-directed fields are associated with more enhanced field strength and solar wind speed as compared to northward flares (Table 1). There exists a positive correlation between the intensification of magnetic turbulence and enhancement in its magnitude when field enhancement is associated with interplanetary shocks [31,32].

Table 1. Forbush decreases, solar wind velocity and interplanetary field enhancement due to solar flares of different field direction at flare sites associated with type-IV radio bursts

Field direction at flare site	Type-IV bursts	No of Flares (x)	Bmax (nT)	Vmax (km/s)	No of Fds (y)	Fd association (y/x)x100%
Southward	Any	58	16.3	601	29	50
Northward	Any	54	11.7	502	11	20
Any	Yes	46	15.5	575	28	61
Any	No	66	12.4	528	12	18
Southward	Yes	32	19.6	639	24	75
Northward	Yes	14	11.4	512	4	28
Southward	No	26	12.9	564	5	19
Northward	No	40	11.9	492	7	17

Another solar phenomena of considerable interest in cosmic ray research is the general magnetic field of the sun, which reverses polarity near every sunspot maximum, going through a complete cycle of 22-years. Two-dimensional models of Forbush decreases using drift effects predict larger decrease amplitude in post-1971 epoch than in pre-1971 epoch [33]. Solar polar field reversed completely in 1971. As our flare data covers two polarity conditions of solar polar magnetic field (1967-70 and 1978-79), we have looked for any difference in decrease amplitude as a result of solar polar field reversal. Figure 3 shows the effect of flares with northward and southward directed fields at flare sites during the period 1967-70 and 1978-79. It is seen from this figure that the decrease in intensity due to southward flares during 1967-70 is almost same as due to flares during 1978-79. Similarly, the decrease amplitudes due to northward flares of 1967-70 and 1978-79 are also equal. These results show that the solar polar field reversal of 1971 has had no marked effect on the amplitude of Forbush decreases.

Le Roux and Potgieter [34, 35] simulated Forbush decreases by assuming that turbulent field regions of enhanced scattering cause them, and drift effects are diminished in regions that originate at the Sun and propagates onward. This model predicts almost same amplitude of decrease in both the polarity conditions of solar polar magnetic fields. Regarding recovery time, two-dimensional models of Forbush decreases [33-35], which include the effects of large-scale gradient and curvature drifts, predict much larger (~2.5 times) recovery time in 1967-70 polarity condition of solar polar magnetic field than in 1978-79 polarity condition. However, when simulation was done by scaling down the drift effects by a factor of 3, though present, the recovery time is much closer in two polarity states. However, the experimental evidences regarding change in recovery time with the reversal of the field remain inconclusive. For example, Lockwood *et al* [23] observed no significant change in the recovery time with the reversal of the field. But, apparently in contrast with conclusions of Lockwood *et al.* [23], two other studies [24, 25] observed that recovery time is less during the condition of solar polarity existing in 1978-79 as compared during opposite polarity condition (*e.g.* 1967-70). The apparent difference of the recovery rate between 1967-70 and 1978-79 can be seen both in Figure 3 (A) and (B). This is consistent with the results of Rana *et al* [25]. It is also in qualitative agreement with the model calculations of Le Roux and Potgieter [34, 35] and Kadokura and Nishida [33].

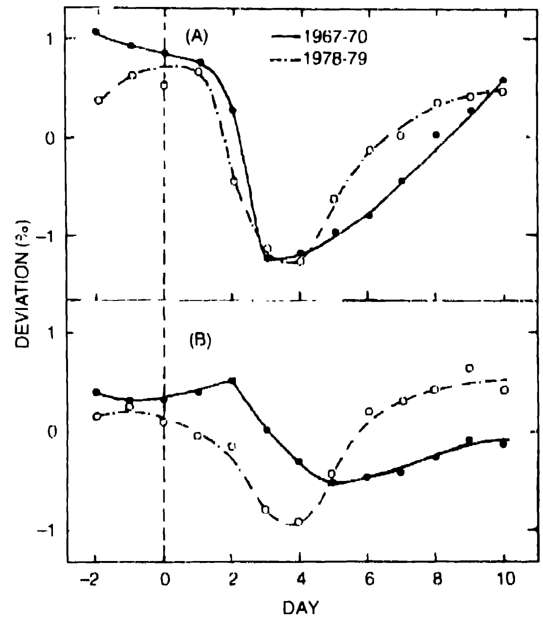

Figure 3. Superposed epoch results of cosmic ray intensity. Epoch days correspond to (A) flares observed in southward directed magnetic field at flare sites during 1967-70 and 1978-79, and (B) flares taking place in northward-directed fields during 1967-70 and 1978-79.

For 1967-70, the northern hemisphere interplanetary magnetic field (IMF) is pointed towards the Sun and for 1978-79, the northern hemisphere IMF is pointed away from the Sun. In the later periods, cosmic rays drift towards the earth from over the solar poles, and under such circumstances, the cavity left behind by the propagating disturbance in the equatorial region, will be filled at a faster rate. This recovery time will be more when solar polarity reverses. Under such condition, particles drift towards earth from the equatorial region and drifting particles will primarily encounter the disturbance head on, and it leads to slower recovery as filling process is retarded in this situation. This is the consequence of drift-dominated models.

The results obtained by us can be explained by suggesting the primary role for enhanced magnetic turbulence as observed in the sheath region (between shock front and ejected plasma cloud) leading to enhanced scattering and smaller diffusion coefficient at and behind shock front, resulting in the rapid development of main phase of Forbush decrease and diffusive propagation from around the shock during the recovery phase. However, it does not exclude the additional role of drifts, at least during the recovery phase of decrease.

Solar parameters (e.g. sunspots, solar flares) and interplanetary parameters (e.g. solar wind velocity and IMF) are considered to represent, directly or indirectly, the conditions prevailing in the interplanetary medium. These parameters have been used to correlate with cosmic ray intensity in order to study the long-term (~11-year and 22 year) and short-term variations (solar flare increases and Forbush decreases). Sunspots themselves have no effect on the earth, but their magnetic field twist and stretch until some instability releases pent-up energy and causes a flare. It has been proposed that the piston driven shock is more likely to be formed when the flare-site magnetic field will be parallel to the global magnetic field of the Sun [36]. Shocks in the interplanetary space are an important element for the worldwide Forbush decreases of cosmic rays. Therefore, it also seems desirable that individual flares, taking place in active regions of different magnetic polarity, and the associated distinct properties are utilized to study the energetics of these flares and their subsequent effects in interplanetary space and their relative importance in producing transient decreases in cosmic rays.

Figure 4 shows the maximum IMF magnitude following solar flares and associated decrease in cosmic ray intensity. The decrease in cosmic ray intensity due to flares which took place in the regions where large-scale magnetic field was directed northward and southward are marked by crosses and solid circles, respectively for the period 1967-70, and by open and filled triangles, respectively for the period 1978-79. These values due to flares associated with type-IV radio bursts (of duration >10 minutes) are encircled. We see from this figure (also see Table 1) that (i) Flares with southward-directed fields are associated with enhanced IMF intensity as compared to northward-directed flares. Moreover, most of the flares following which the IMF magnitude increases to >15 Gamma are associated with type-IV radio bursts; (ii) Transient decrease (amplitude > 2%) are rarely found to be associated with flares which took place in northward directed fields and/or not associated with type-IV radio burst; (iii) The decrease amplitude in cosmic ray intensity produced by flares which took place in southward directed magnetic field is higher compared to the decrease amplitude due to flares which took place in northward directed magnetic field. Almost all the decreases of large amplitude (> 4%) are produced by flares associated with type-IV radio bursts, (iv) Though there is scatter in data points, in general, higher amplitude decrease is associated with flares following by larger IMF magnitude.

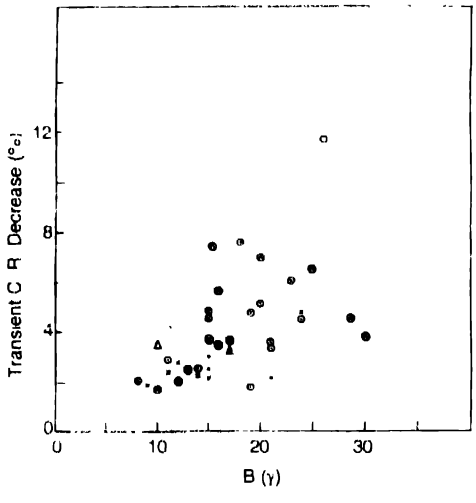

Figure 4. Interplanetary magnetic field strength and cosmic ray intensity decrease due to solar flares (with different orientation and associated/not associated with type-IV radio bursts).

In Figure 5, we have shown the cosmic ray decrease amplitude and corresponding maximum solar wind velocities following flares which took place in northward/southward directed magnetic fields. The symbols used in this figure are same as in Figure 4. From this figure, we observe that the majority of the flares whose large-scale magnetic field were directed southward (and specially those also associated with type-IV radio bursts) produce larger increase in velocity than those whose large-scale magnetic field was directed northward. Further, the decrease amplitude is, in general, higher for higher velocities of the solar wind, which is more frequently observed following southward flares associated with type-IV radio bursts.

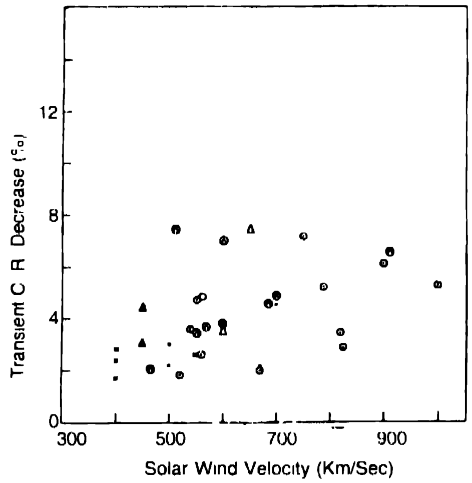

Figure 5. Effect of solar flares on increase in solar wind velocity and decrease in cosmic ray intensity

In Figure 6, heliographic latitude of flares and consequent decrease in cosmic ray intensity is shown. No appreciable dependence of the decrease amplitude upon flare latitude is seen. However, the number of decreases associated with northern flares and majority of Forbush decreases with large decrease amplitude (>4%) are also associated with these flares. These differences may be due to the fact that north-south asymmetry in solar activity is positive during the periods considered for this analysis and the north-south asymmetry increases with the area and importance of flares, [37], as well as their energy output [38].

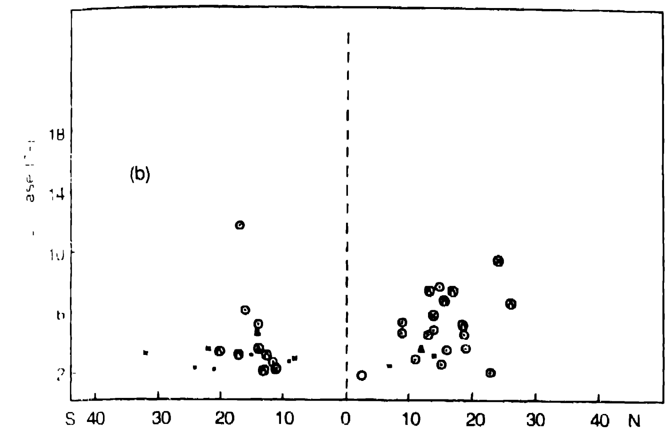

Figure 6. Latitudinal position of solar flares and their effectiveness in reducing cosmic ray intensity

In Figure 7, the longitudinal position of flares producing transient decreases in cosmic ray intensity is shown. Though no clear dependence of the decrease amplitude on solar flare longitude can be inferred (probably due to smaller number of cases) from this figure, it is seen that some Forbush decreases of larger decrease amplitude are associated with solar flares occurring in the center-east region of the solar disk. All of them are associated with type-IV bursts, in agreement with the results of Refs [2, 39] This result is consistent with the findings that Forbush decreases with large decrease amplitude will be observed when the shocks followed by ejecta are encountered [6,11,40]

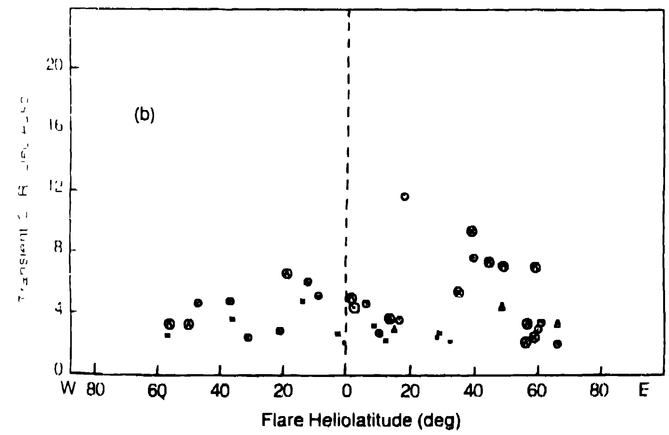

Figure 7. Longitudinal position of solar flares and their effectiveness in reducing cosmic ray intensity.

Most dramatic interplanetary disturbances are often associated with big solar flares. Interplanetary shock waves driven by solar flare ejecta arrive at earth one to four days after the onset of flare at the solar disk. This kind of flare plasma ejecta usually carries with it a magnetic field with an orientation at the flare site. It often happens that the passage of the shock front is followed some hours (~15± 3) later by tangential discontinuity that separates the hot, shocked and turbulent ambient plasma from the plasma ejecta that act like a piston. The formation of piston driven shocks and energy of type-IV radio bursts depends on the flare site magnetic field [36]. The type-IV burst signifies the ejection of an energetic plasma cloud by the flares. This plasma cloud proceeded by a turbulent plasma sheath and shock front is expected to produce transient decrease in cosmic ray intensity. It has been shown that the shocks observed to be followed by ejected plasma cloud are more frequently associated with Forbush decreases than those not associated with such ejecta [40]. Underlying reason for this difference in cosmic ray effects of interplanetary shocks is that the former is accompanied by (magnetically) more turbulent sheath than the latter [6]

From the above discussed results, we could make a possible scenario for producing Forbush decreases with solar flares Energetic coronal mass ejections (CMEs) are associated with solar flares and type IV emission is known to be associated with mass ejections Type-IV radio burst signifies the ejection of a plasma cloud that is energetic enough to drive an interplanetary shock and turbulent sheath of ambient plasma. The ejected plasma cloud usually carries with it magnetic field with an orientation determined by direction of magnetic field at flare site. If large-scale field at flare site is directed southward, the flare will produce greater solar wind disturbance. Most of the flares with southward-directed fields are associated with SSC (geomagnetic signature of interplanetary shocks) and with more enhanced interplanetary magnetic field suggesting that the field in shocked plasma (sheath) is more turbulent. Hence, larger intensity reduction can be expected for southward-directed fields due to enhanced particle scattering. However, particle drifts play a role during recovery to pre-decrease level.

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